

Extended Abstract

# Automated Design of the Europa Orbiter Tour

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**In this paper we investigate tours of the Jovian satellites Europa, Ganymede, and Callisto for the Europa Orbiter Mission. The principal goal of the tour design is to lower arrival  $V_{\infty}$  for the final Europa encounter while meeting all of the design constraints. Key constraints arise from considering the total time of the tour and the radiation dosage of a tour. These tours may employ 14 or more encounters with the Jovian satellites, hence there is an enormous number of possible sequences of these satellites to investigate. We develop a graphical method that greatly aids the design process.**

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## Introduction

The Europa Orbiter Mission is currently planned for launch in 2003. The mission will investigate the possibility that liquid oceans may exist beneath the surface ice of Europa. It will attempt to map these regions of liquid water for follow-up missions to Europa. The recent discovery of life in the ice of Lake Vostok, a lake deep beneath the Antarctic ice cap, lends impetus to Europa missions with the suggestion that life may be possible on Europa [1].

In order to place the spacecraft into orbit about Europa, the arrival  $V_\infty$  must be reduced as much as possible prior to orbit insertion. This paper investigates the problem of lowering the arrival  $V_\infty$  with a tour (i.e. a sequence of gravity assists) of the Jovian satellites, Europa, Ganymede, and Callisto.

This tour is only one phase of the Europa Orbiter mission. After arriving at Jupiter, a maneuver will be performed to capture the spacecraft about Jupiter in an orbit that encounters Ganymede. Our tours start with variations of this Ganymede encounter. After the tour reduces the final arrival  $V_\infty$  at Europa, the endgame begins. The endgame is designed by the Jet Propulsion Laboratory (JPL) to use a combination of Europa flybys, small maneuvers, and 3 body effects to reduce the energy of the orbit further prior to the orbit insertion maneuver (See Johannesen [2]).

## Constraints for Tour Design

We start with a set of initial conditions at Ganymede, which vary depending on when the Orbiter is launched from Earth. JPL categorizes these conditions as “late,” “middle,” and “early” launch period. Typical initial conditions from each launch period are included in Table 1. Starting from initial conditions such as those in Table 1, we then proceed to design the tour subject to various constraints.

**Table 1 Initial Conditions at Ganymede**

<b>Launch Period<sup>1</sup></b>	<b><math>V_{\infty}</math> (km/s)</b>	<b>Periapsis (<math>R_J</math>)</b>	<b>Period (days)</b>
Early	8.18	9.8	200.2
Middle	8.47	9.4	199.7
Late	8.14	9.8	191.4

<sup>1</sup> Launch period ranges from 11/10-11/25/2003, and results in arrivals at Jupiter from 2/28 to 12/05/2007.

There are many constraints that must be met by the tour. Most important is to have as low a  $V_{\infty}$  at Europa as possible. Based on the Hohmann transfer from Ganymede to Europa the lowest ballistic  $V_{\infty}$  achievable is 1.49 km/sec. Periapsis of any orbit in the tour must be greater than 8.8  $R_J$  (Jovian radii), to mitigate the effects of radiation exposure. Flyby altitude at each satellite must be greater than 100 km at each satellite in general, and must be greater than 200 km during the first flyby of any satellite, in order to avoid crashing into the surface due to navigational uncertainties. While in transit between any two satellites, the spacecraft must not approach within 50,000 km of any third body (i.e. a “non-targeted” flyby) in order to avoid perturbing the orbit too much. Another design constraint is to minimize the total number of flybys, since each flyby may require a slight correctional delta-V. No close flybys are allowed when Jupiter is in solar conjunction. It is highly desired that the tour should be completed while the spacecraft is within 5 AU of the Earth. The combination of solar conjunction constraint and 5 AU constraint limits the time of flight for the tour to a period that varies from roughly 200 to 500 days, depending on whether the tour is from the late, middle or early launch period. Each leg of the tour must pass through apoapsis to allow for trajectory correction maneuvers. Finally, each tour must end in a resonant orbit with Europa.

The endgame follows the tour. The endgame consists of a series of Europa flybys combined with a maneuver at apoapsis [2]. The maneuvers raise perijove and lower  $V_{\infty}$ , while the flybys reduce the period. There is a maximum  $V_{\infty}$  desired for a given final resonance from the tour, as shown in Table 2. For example, for a 4:3 resonance (4 spacecraft revs : 3 Europa revs)

the arrival  $V_\infty$  at Europa should not exceed 1.8 km/sec. On the other hand, a 6:5 resonance requires a  $V_\infty$  of less than 1.2 km/sec, which is not achievable ballistically. Since it is possible to achieve less than 1.8 km/sec at Europa for the 4:3 resonance, most Tours end with a 4:3 resonance.

**Table 2 Maximum  $V_\infty$  Allowed for Given Resonance [3]**

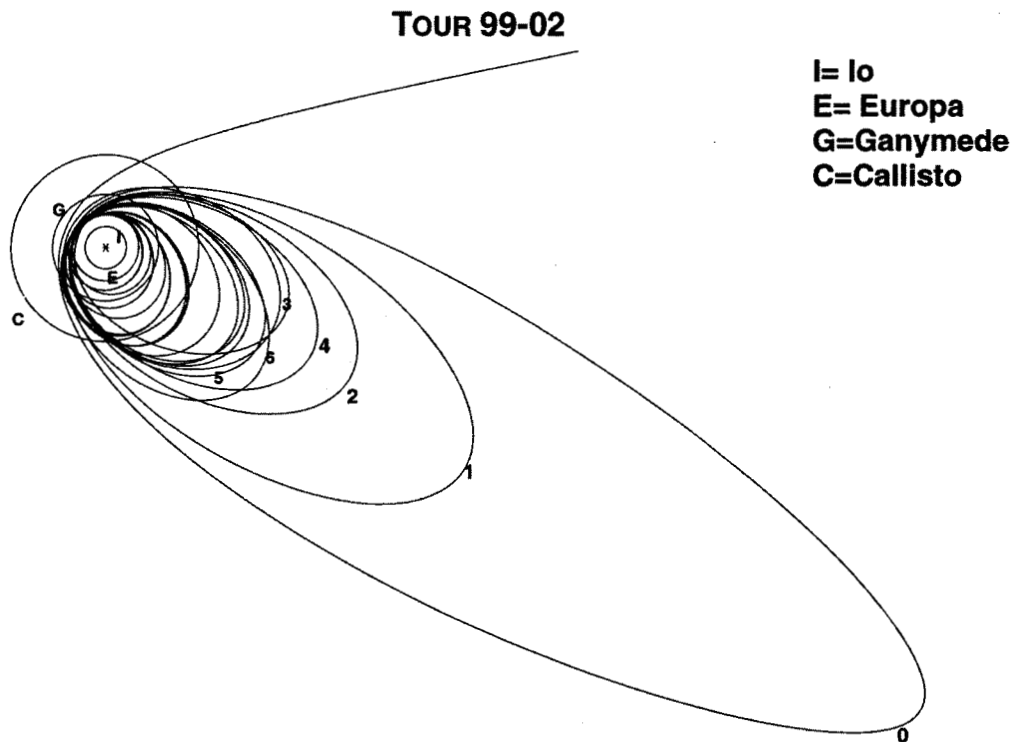
<b>Resonance</b>	<b><math>V_\infty</math> (km/s)</b>
3:1	3.2
5:2	3.6
2:1	3.0
5:3	3.1
4:3	1.8
6:5	1.2

## Solution Approach

STOUR (Satellite Tour Design Program) is a software tool that was developed by JPL for the Galileo mission tour design [4]. It has been enhanced and extended at Purdue to enable the automated design of gravity-assist tours in the Solar System as well as the satellite system of Jupiter [5-8]. STOUR uses the patched conic method to calculate all gravity-assist trajectories meeting specified requirements.

We use STOUR as our principal tool for the design of Europa Orbiter tours. From a starting condition at Ganymede, STOUR finds trajectories using a specified path, i.e. a sequence of gravity-assist bodies. The massive number of trajectories produced by STOUR must be then sifted through to find viable tour candidates.

Tour 99-02 (the second tour we discovered in 1999) uses 15 flybys of Europa, Ganymede, and Callisto (Figure 1) [8,9]. Even with the initial position and velocity specified, there are tens of thousands of possible tours that follow a specified path. The calculation of these can take weeks for a single path. When we consider that there are  $3^{13}$  (1.6 million) possible paths that begin at Ganymede and reach Europa in 15 flybys, we see that the problem of calculating all possible tours is intractable with current computer technology. Clearly, we need to know what paths have the most promise to yield viable tour candidates before even beginning an STOUR run.



**Figure 1 Tour 99-02**

We began tackling this problem by choosing paths by trial and error tempered with engineering judgement. For instance, we could lower the spacecraft's period and thus decrease the total energy relative <sup>to</sup> Jupiter in an attempt to reduce our final arrival  $V_{\infty}$  at Europa. A series of pump-downs with Ganymede would accomplish this quickly, but would also quickly lower the

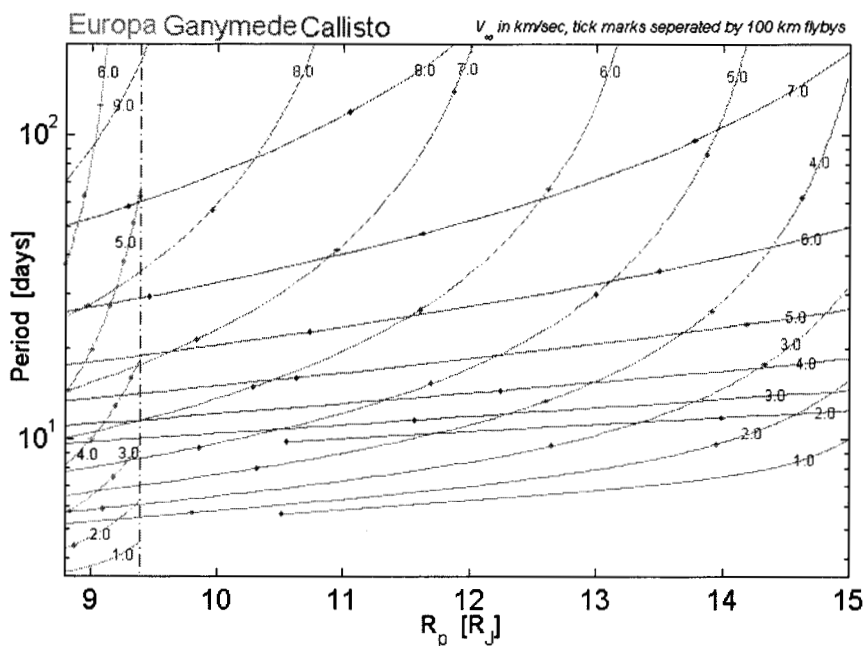
periapsis into the hazardous radiation environment (i.e. fry the spacecraft). We could then modify this path to include Europa and Callisto. Following such logic, we found that although Europa has less gravity to assist us, it is able to reduce period more than Ganymede for the same decrease in periapsis height. We also noticed that Callisto is very handy for raising periapsis, as it can do so with the lowest cost in increased orbit period. If we combined these satellites in the right order (e.g. Ganymede-Callisto or Ganymede-Europa-Callisto), we could reduce period and periapsis at the end of a sequence of satellites. The identification of useful path segments such as these took months of experience with the problem.

To improve this trial and error method, we next conducted exhaustive searches through all possible five-body path segments for the beginning of the tour. Even limiting the paths to five bodies left us with a computationally intensive and time consuming process which needed to be repeated for each different initial condition at the first Ganymede encounter. Moreover, the results of this endeavor were then hard to interpret. A key question is how to characterize what will end up being a good tour after only five flybys. One figure of merit is  $V_{\infty}$ , but it is difficult to draw comparisons between the final  $V_{\infty}$ 's of path segments ending at different satellites.

During the initial process we found that tracking both period and periapsis could often identify interesting path segments. Since the satellites we are working with are in almost circular orbits about Jupiter, period and periapsis prescribe both the spacecraft's orbit about Jupiter and the  $V_{\infty}$  at each satellite.

This observation suggests the "P-r<sub>p</sub>" plot (Figure 2). This is a plot of period versus periapsis for period less than 200 days that meet the periapsis constraint ( $> 8.8 R_J$ ) and are able to transfer between at least two gravity assist bodies. The plot shows contours of constant  $V_{\infty}$  for each satellite, assuming circular, coplanar orbits. A gravity assist rotates the  $V_{\infty}$  vector of the spacecraft along one of these contours modifying the orbit about Jupiter. Where contours from different satellites intersect, there exists a transfer between those satellites. These contours give

the values of  $V_\infty$  at each satellite for this transfer arc. This provides a method for comparing the  $V_\infty$  at different bodies.



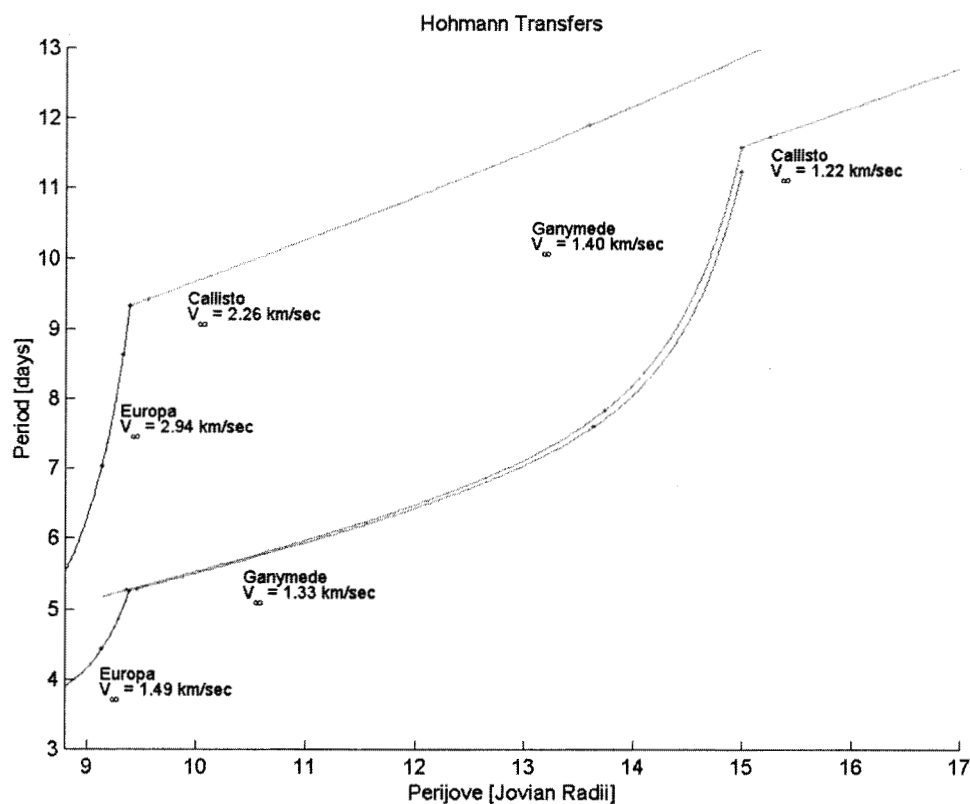
**Figure 2 P-r<sub>p</sub> Plot**

If we constrain the flybys to have a minimum altitude of 100 km above the surface of the satellite, we are limited in how far we can travel along a contour in one flyby. This is illustrated on the plot by tick marks. From one tick mark on a contour we may move a maximum of the distance to the next tick mark up or down that contour. The tick marks also can help us judge how far one flyby can move up or down a contour even when not starting from a tick mark.

We can now see on the plot in a few minutes what before took months. Remembering that our goal with the tours is to decrease the spacecraft's period but still keep the periapsis high, we can see that Europa is most effective in lowering period with a minimal cost in periapsis height by the slope of its  $V_\infty$  contours. However, due to the distance between the tick marks, Ganymede is much more effective in lowering period with a single flyby. The slope of Callisto's contours show that it is the best choice for raising periapsis as it costs the least in terms of increased period to do so.

With one of these charts and a pencil, a tour designer can quickly sketch out a promising path for analysis in STOUR. Also, known tours can be plotted and examined for possible improvements.

Figure 3 shows the Ganymede-Europa, Callisto-Ganymede, and Callisto-Europa Hohmann transfers. These orbits provide a lower bound of 1.49 km/sec for arrival  $V_{\infty}$  at Europa. The chart shows this can only be achieved via multiple Ganymede-Europa arcs at the end of a tour as opposed to directly after a Callisto flyby.



**Figure 3 Hohmann Transfers**

We are currently extending this method to search for the fastest possible path to Europa as well as low radiation paths to Europa. This involves developing software to automatically traverse the P- $r_p$  plots to find possible paths and calculate a cost for those paths.



## Results

At this point we have been able to generate 35 tours for the Europa Orbiter Mission [8]. The lowest arrival  $V_{\infty}$  at Europa for a tour meeting the constraints, so far, is 1.62 km/sec. The full paper will discuss at least two tours in detail. We will discuss some of the most attractive features of the best tours in terms of time of flight, radiation dosage and a combination of these two considerations as well.

## References

- [1] D. M. Karl, D. F. Bird, K. Björkman, T. Houlihan, R. Shackelford, and L. Tupas, "Microorganisms in the Accreted Ice of Lake Vostok, Antarctica," *Science*, Dec 10 1999: 2144-2147.
- [2] Johannesen, J. R., and D'Amario, L. A., "Europa Orbiter Mission Trajectory Design", AAS 99-360, AAS/AIAA Astrodynamics Specialists Conference, Girdwood, AK, August 1999.
- [3] Johannesen, J. R., Jet Propulsion Lab, Pasadena, Ca., personal communication, July 1999.
- [4] Rinderle, E. A., "Galileo User's Guide, Mission Design System, Satellite Tour Analysis and Design Subsystem," Jet Propulsion Laboratory, Pasadena, CA, JPL D-263, 1986.
- [5] Williams, S. N., "Automated Design of Multiple Encounter Gravity-Assist Trajectories," Master's Thesis, School of Aeronautics and Astronautics, Purdue University, 1990.
- [6] Longuski, J. M. and Williams, S. N., "Automated Design of Gravity-Assist trajectories to Mars and the Outer Planets," *Celestial Mechanics and Dynamical Astronomy*, Vol. 52, No. 3, 1991, pp. 207-220.
- [7] Patel, M. R., "Automated Design of Delta-V Gravity-Assist Trajectories for Solar System Exploration," Master's Thesis, School of Aeronautics and Astronautics, Purdue University, 1993.
- [8] Bonfiglio, E. P., "Automated Design of Gravity-Assist and Aerogravity-Assist Trajectories" Master's Thesis, School of Aeronautics and Astronautics, Purdue University, 1999.
- [9] Bonfiglio, E. P., Strange, N. J., Heaton, A. F., Longuski, J. M., "Low-Thrust and Gravity-Assist Trajectory Design for Planetary Missions," Progress Report #9: Europa Orbiter Tour Design, JPL Contract # 961211.

- [10] Petropoulos, A. E, Longuski, J. M., and Bonfiglio, E. P., "Trajectories to Jupiter via Gravity Assists from Venus, Earth, and Mars," AIAA Paper 98-4284, Aug. 1998.
- [11] Sims, J. A., "Delta-V Gravity-Assist Trajectory Design: Theory and Practice," Doctoral Thesis, School of Aeronautics and Astronautics, Purdue University, 1996.
- [12] Diehl, R. E, and Myers, M. R., "Gravity-Assist Trajectories to the Outer Solar System," Jet Propulsion Laboratory, Pasadena, CA, JPL D-4677, 1987.